Theoretical overview of quarkonium and dilepton production

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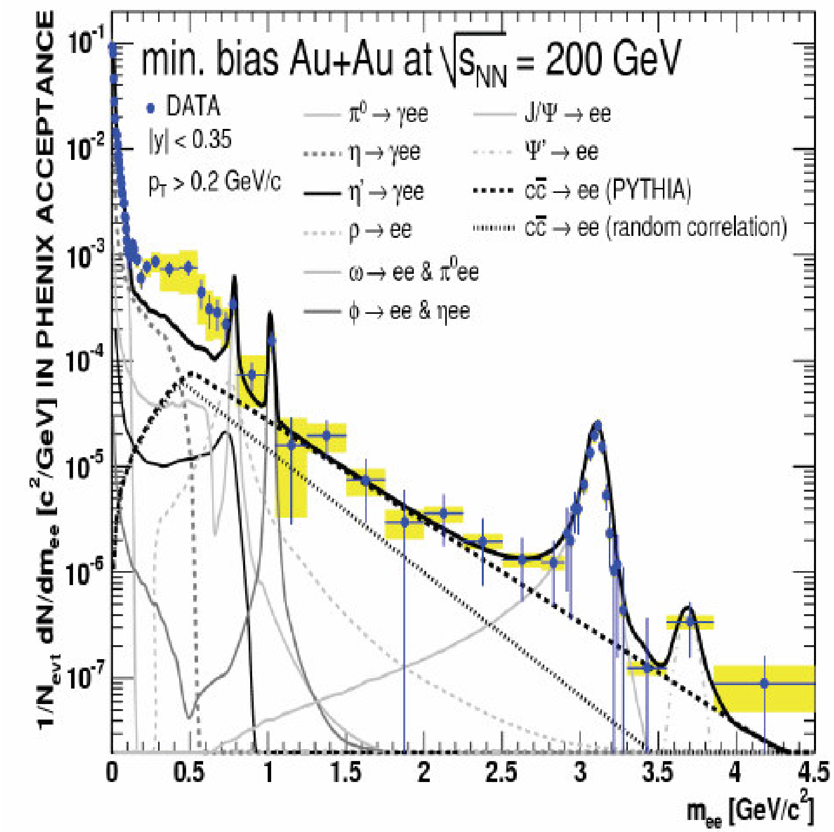
Unlike flow and high p_T suppression quarkonia and thermal dileptons are expected to give more direct information about the chiral and deconfinement transition in QCD as well collective properties of matter produced in RHIC

Melting of quarkonium states : signal for deconfinement and onset of color screening
Matsui and Satz, 1986

Thermal dileptons : direct measurement of the temperature of the produced matter, test consequences of chiral symmetry restoration

PHENIX

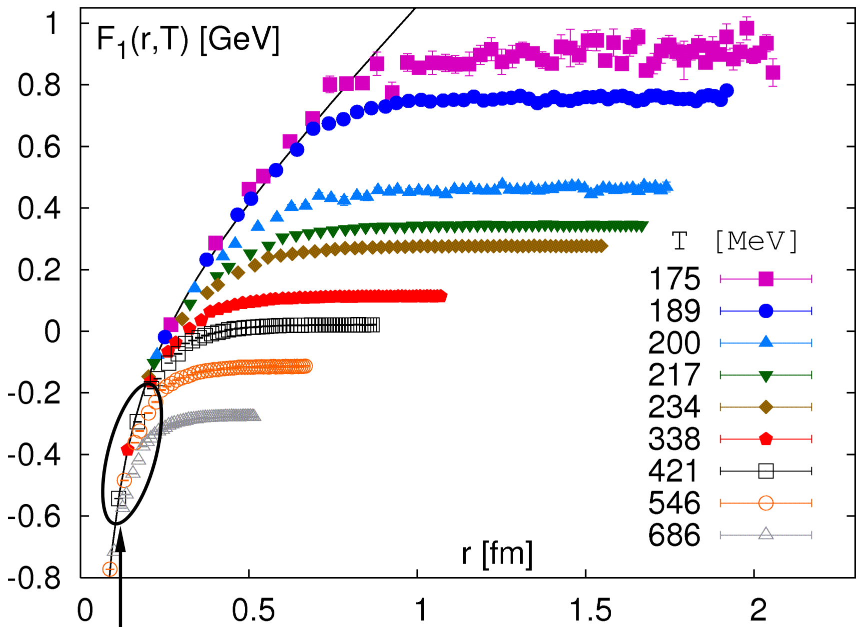


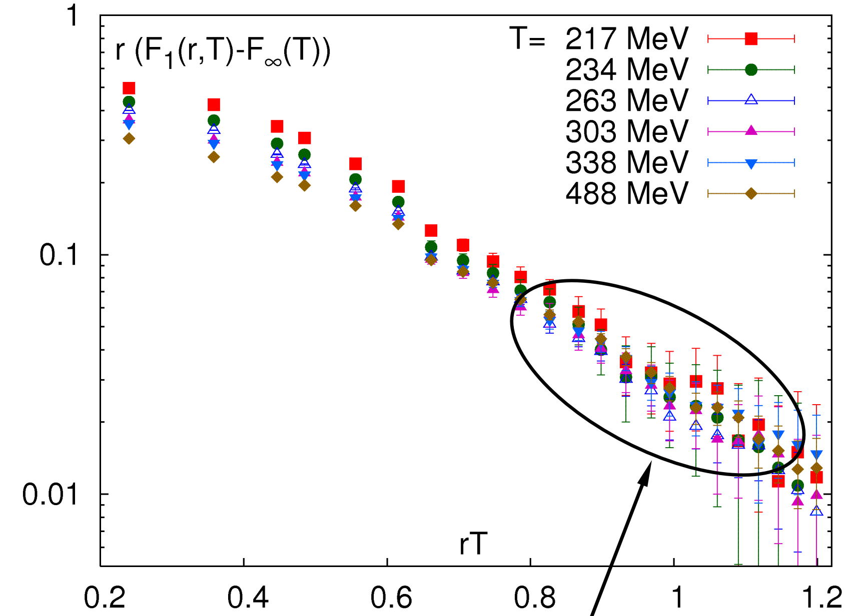
DNP 2010, Santa Fe, November 2-6, 2010

Color screening in lattice QCD

p4 action, $(2+1)-$flavor QCD, $16^3 \times 4$ lattices, $m_\pi \simeq 220$ MeV

P.P., JPG 37 (10) 094009 ; arXiv:1009.5935





$F_1(r,T)$ T-independent at short distances

$F_1(r,T)$ scales with T and is exponentially screened for $r > 0.8/T$

Significant temperature dependence of the static quark anti-quark free energy for $r \simeq 0.3 - 0.5$ fm.

⇓

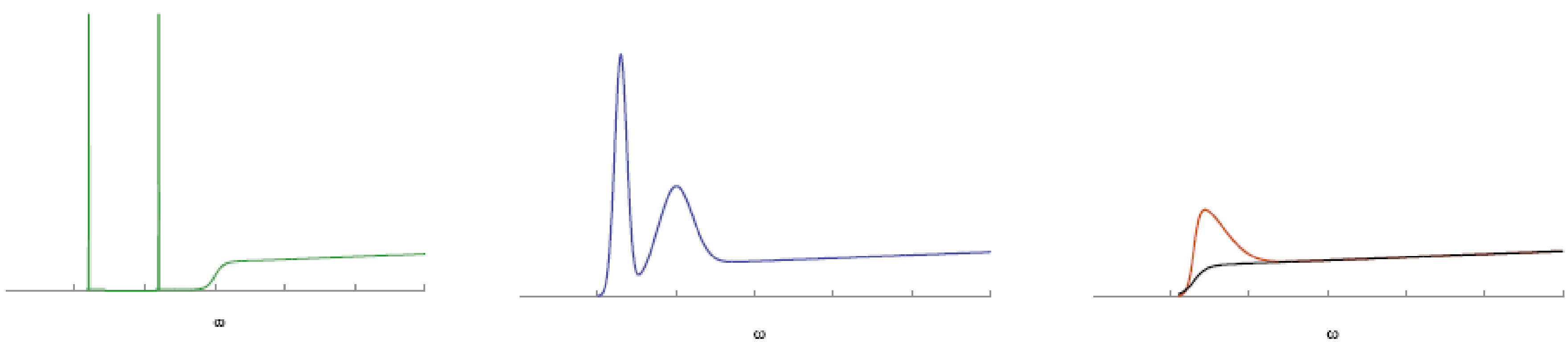
charmonium melting @ RHIC Digal, P.P., Satz, PRD 64 (01) 094015

Quarkonium spectral functions

In-medium properties and/or dissolution of quarkonium states are encoded in the spectral functions

$$\sigma(\omega,p,T) = \frac{1}{2\pi}\,\mathrm{Im}\int_{-\infty}^{\infty} dt e^{i\omega t}\int d^3x e^{ipx}\langle[J(x,t),J(x,0)]\rangle_T$$

Melting is see as progressive broadening and disappearance of the bound state peaks



Due to analytic continuation spectral functions are related to Euclidean time quarkonium correlators that can be calculated on the lattice

$$G(\tau,p,T) = \int d^3x e^{ipx}\langle J(x,-i\tau),J(x,0)\rangle_T$$

$$G(\tau,p,T) = \int_0^{\infty} d\omega\sigma(\omega,p,T)\frac{\cosh(\omega\cdot(\tau-\frac{1}{2T}))}{\sinh(\omega/(2T))}$$

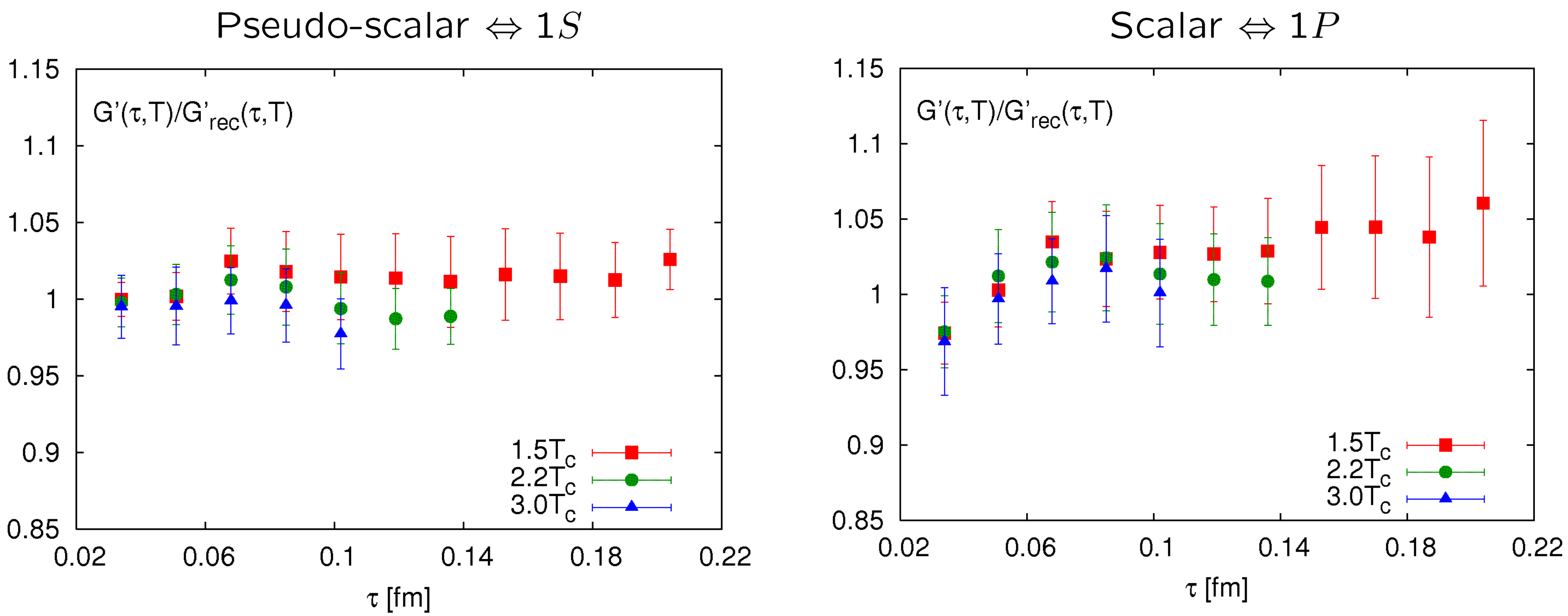
MEM → $\sigma(\omega,p,T)$

1S charmonium survives to $1.6T_c$??

Umeda et al, EPJ C39S1 (05) 9, Asakawa, Hatsuda, PRL 92 (2004) 01200, Datta, et al, PRD 69 (04) 094507, ...

Charmonium correlators at $T>0$

zero mode contribution is not present in the time derivative of the correlator
Umeda, PRD 75 (2007) 094502



P.P., EPJC 62 (09) 85

the derivative of the scalar correlators does not change up to $3T_c$, all the T-dependence was due to zero mode

⇓

either the 1P state (χ_c) with binding energy of *300*MeV can survive in the medium with $\varepsilon=100$GeV/fm^3

or temporal quarkonium correlators are not very sensitive to the changes in the spectral functions due to the limited $\tau_{max}=1/(2\ T)$

Spatial charmonium correlators

Spatial correlation functions can be calculated for arbitrarily large separations $z \to \infty$

$$G(z,T) = \int_0^{1/T} d\tau \int dxdy \langle J(\mathbf{x},-i\tau), J(\mathbf{x},0)\rangle_T, \quad G(z\to\infty,T) \simeq Ae^{-m_{scr}(T)z}$$

but related to the same spectral functions $G(z,T) = \int_{-\infty}^{\infty} e^{ipz} \int_0^{\infty} d\omega \frac{\sigma(\omega,p,T)}{\omega}$

Low T limit :

$$\sigma(\omega,p,T) \simeq A_{mes}\delta(\omega^2 - p^2 - M_{mes}^2)$$

$$A_{mes} \sim |\psi(0)|^2 \to m_{scr}(T) = M_{mes}$$

$$G(z,T) \simeq |\psi(0)|^2 e^{-M_{mes}(T)z}$$

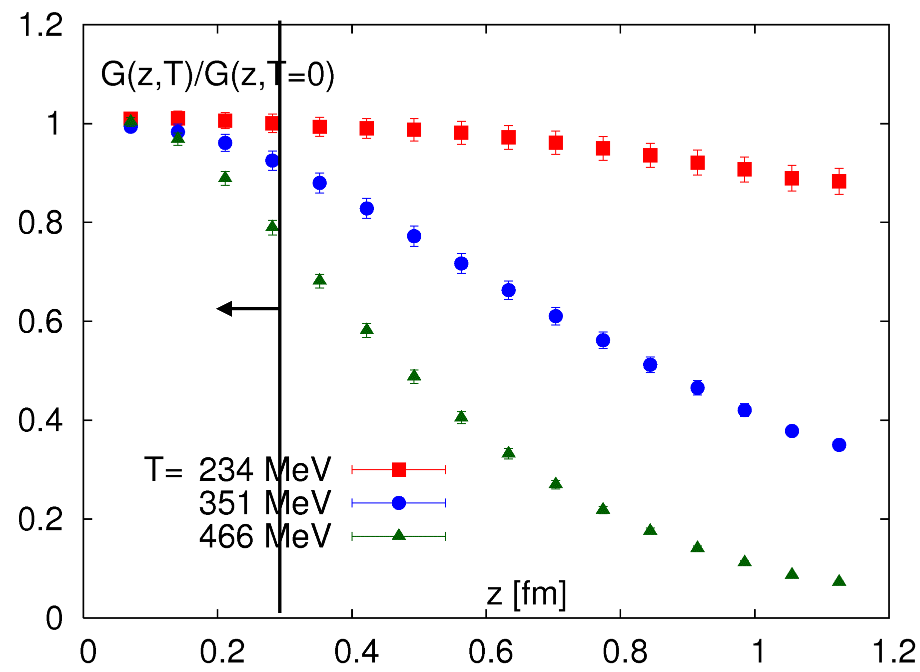
High T limit :

$$m_{scr}(T) \simeq 2\sqrt{m_c^2 + (\pi T)^2}$$

p4 action, dynamical *(2+1)-f* *32*^{3}x*8* and *32*^{3}x*12* lattices

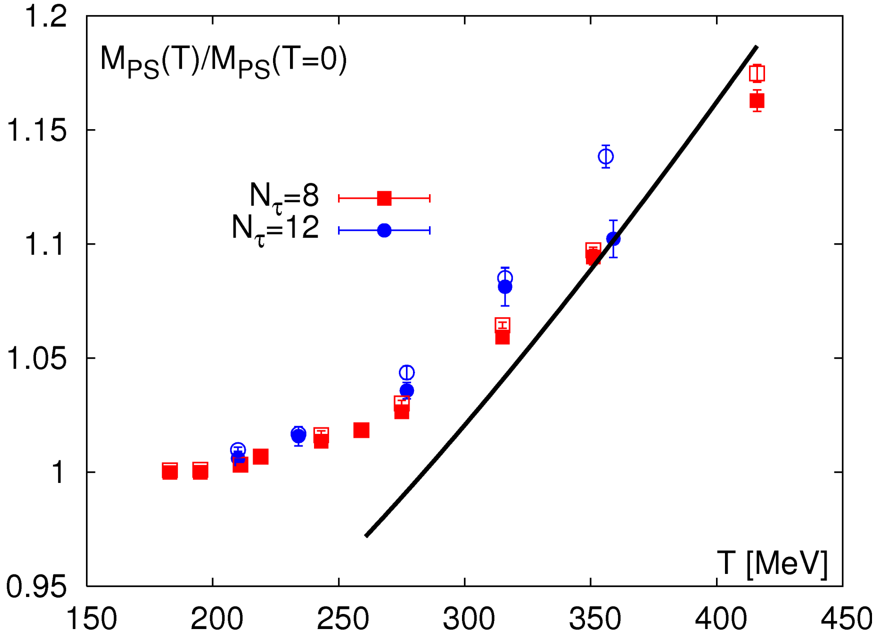
Significant temperature dependence already for *T=234* MeV, large *T*-dependence in the deconfined phase

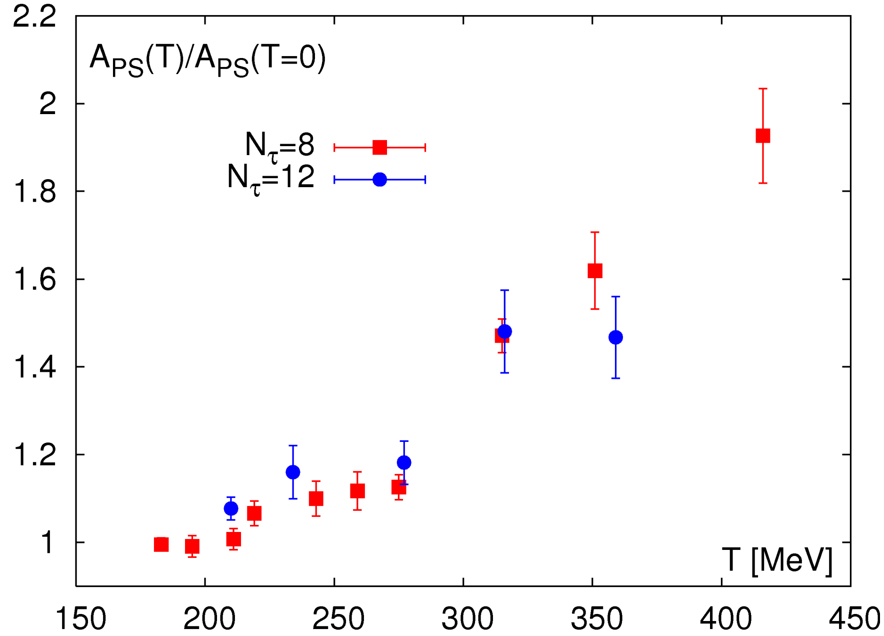
For small separations *(z T<1/2)* significant *T*-dependence is seen



Spatial charmonium correlators

pseudo-scalar channel => 1S state , point sources: filled; wall sources: open





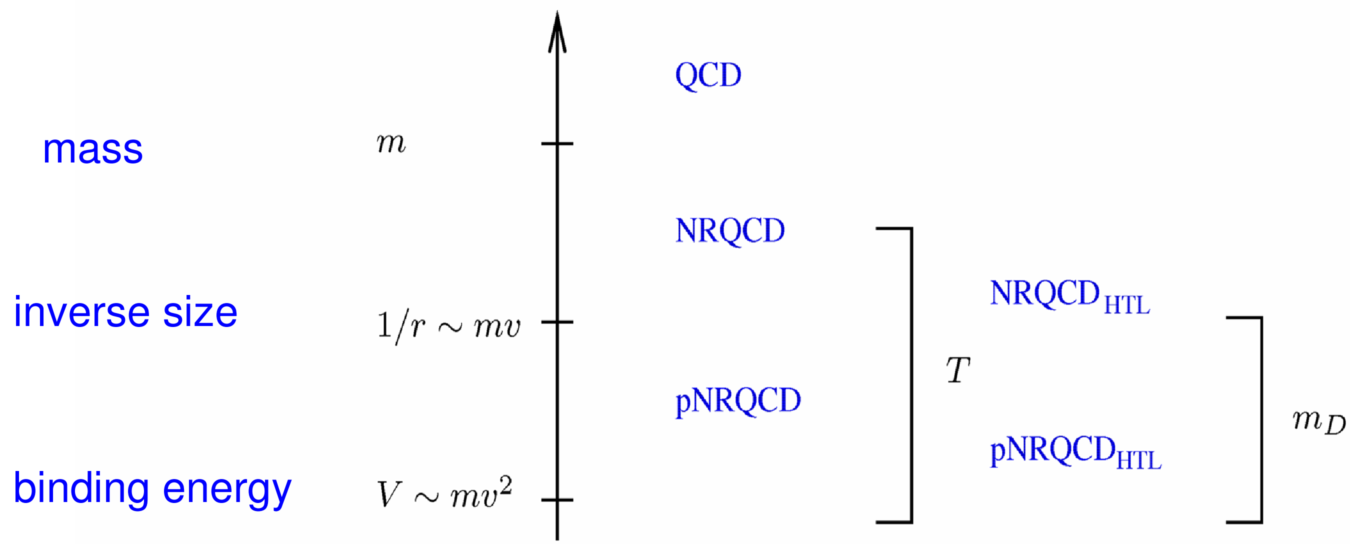
- no *T*-dependence in the screening masses and amplitudes (wave functions) for ***T<200* MeV**

- moderate *T*-dependence for ***200<T<275* MeV** => medium modification of the ground state

- Strong *T*-dependence of the screening masses and amplitudes for ***T>300* MeV**, compatible with free quark behavior assuming **m_c=*1.2* GeV** => dissolution of 1S charmonium !

Effective field theory approach for heavy quark bound states and potential models

The heavy quark mass provides a hierarchy of different energy scales



The scale separation allows to construct sequence of effective field theories:
NRQCD, pNRQCD

Potential model appears as the tree level approximation of the EFT
and can be systematically improved

pNRQCD at finite temperature

EFT for energy $E_{bind} \sim m\,v^2$

Ultrasoft quark and gluons

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \sum_{i=1}^{n_f} \bar{q}_i\, i \not{D} q_i$$

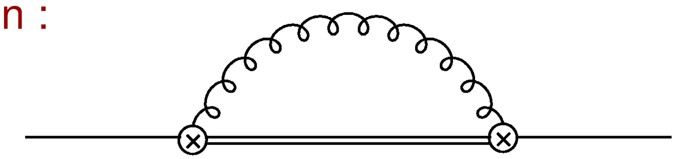
Singlet $Q\bar{Q}$ field — Octet $Q\bar{Q}$ field

$$+ \int d^3r\ \mathrm{Tr}\left\{ \mathrm{S}^\dagger \left[i\partial_0 - \frac{-\nabla^2}{m} - V_s(r,T) \right] \mathrm{S} + \mathrm{O}^\dagger \left[iD_0 - \frac{-\nabla^2}{m} - V_o(r,T) \right] \mathrm{O} \right\}$$

$$+ V_A\, \mathrm{Tr}\left\{ \mathrm{O}^\dagger \vec{r}\cdot g\vec{E}\,\mathrm{S} + \mathrm{S}^\dagger \vec{r}\cdot g\vec{E}\,\mathrm{O} \right\} + \frac{V_B}{2} \mathrm{Tr}\left\{ \mathrm{O}^\dagger \vec{r}\cdot g\vec{E}\,\mathrm{O} + \mathrm{O}^\dagger \mathrm{O}\vec{r}\cdot g\vec{E} \right\} + \ldots$$

If $E_{bind} < T$ there are thermal contribution to the potentials : $V_s(r) \to V_s(r) + \delta V_s(r,T)$

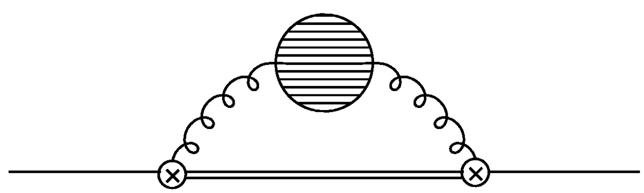
singlet-octet transition :



$\mathrm{Re}\,\delta V_s(r) \ \sim \alpha_s^2 T^2 r$

$\mathrm{Im}\,\delta V_s(r) \sim \alpha_s^3 T$

Landau damping :



$\mathrm{Re}\,\delta V_s(r,T) \sim \mathrm{Im}\,\delta V_s(r,T)$

$\sim \alpha_s T^3 r^2 \times \left(\frac{m_D}{T}\right)^n$

Brambilla, Ghiglieri, P.P., Vairo, PRD 78 (08) 014017

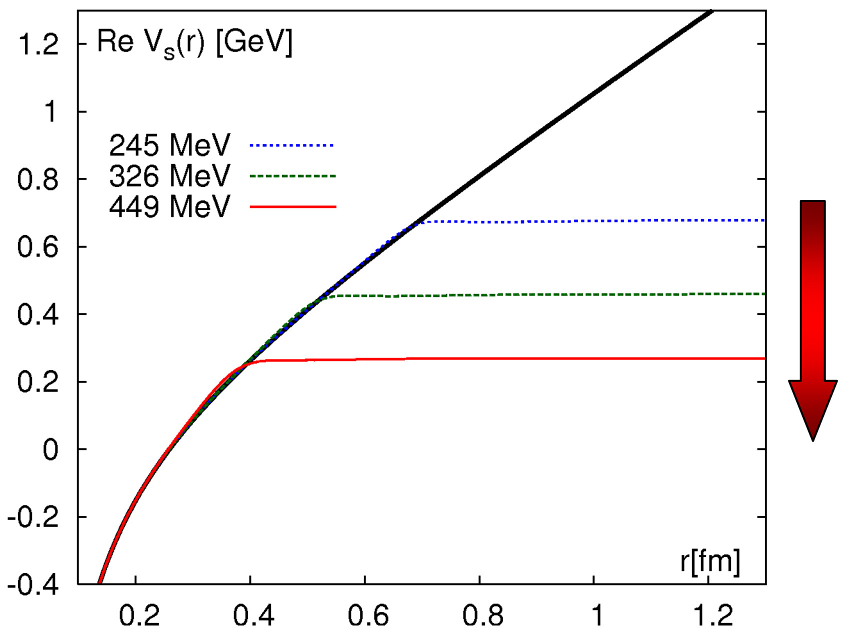
pNRQCD beyond weak coupling and potential models

Above deconfinement the binding energy is reduced and eventually $E_{bind} \sim mv^2$ is the smallest scale in the problem (zero binding) $mv^2 >> \Lambda_{QCD}, 2\pi T, m_D$ => most of medium effects can be described by a T-dependent potential

Determine the potential by non-perturbative matching to static quark anti-quark potential calculated on the lattice

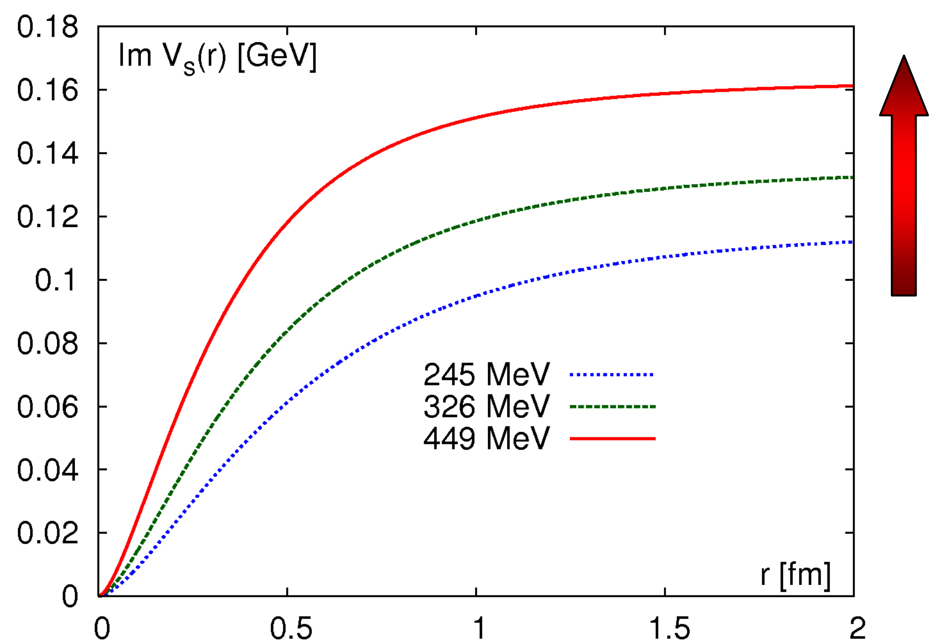
Caveat : it is difficult to extract static quark anti-quark energies from lattice correlators => constrain $\mathrm{Re}V_s(r)$ by lattice QCD data on the singlet free energy, take $\mathrm{Im}V_s(r)$ from pQCD calculations

"Maximal" value for the real part



Mócsy, P.P., PRL 99 (07) 211602

Minimal (perturbative) value for imaginary part



Laine et al, JHEP0703 (07) 054,
Beraudo, arXiv:0812.1130

Lattice QCD based potential model

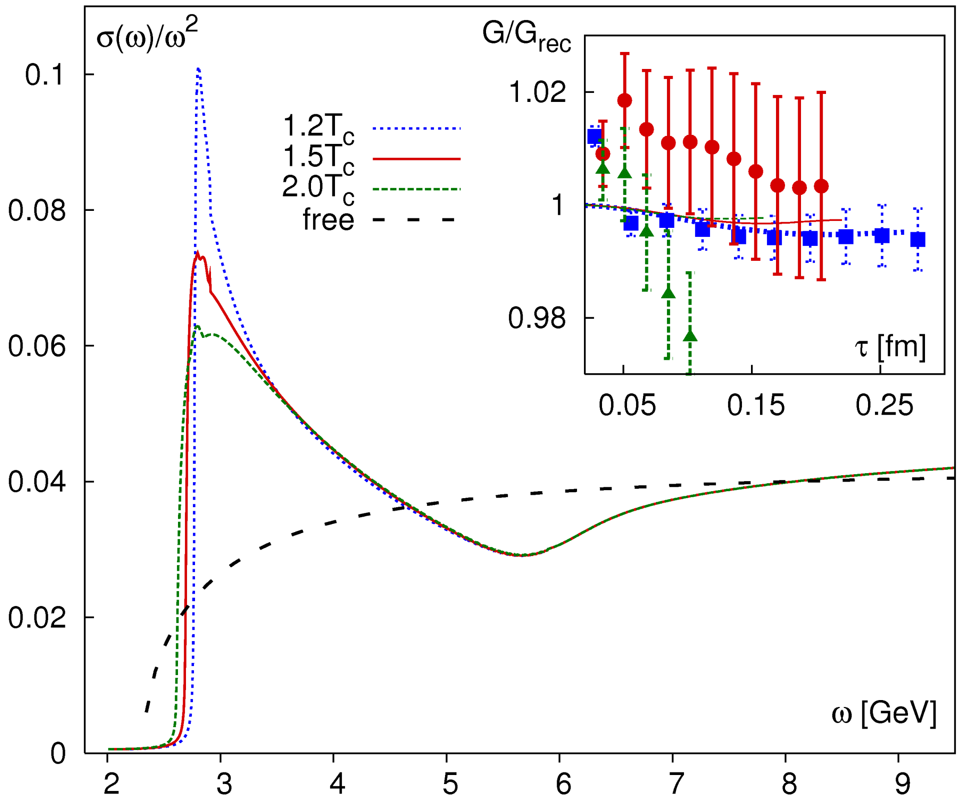
If the octet-singlet interactions due to ultra-soft gluons are neglected :

$$\left[i\partial_0 - \frac{-\nabla^2}{m} - V_s(r,T) \right] S(r,t) = 0 \quad \Rightarrow \quad \sigma(\omega, T)$$

potential model is not a model but the tree level approximation of corresponding EFT that can be systematically improved

Test the approach vs. LQCD : quenched approximation, $F_1(r,T) < \mathrm{Re}V_s(r,T) < U_1(r,T)$, $\mathrm{Im}V(r,T) \approx 0$

Mócsy, P.P., PRL 99 (07) 211602, PRD77 (08) 014501, EPJC ST 155 (08) 101



- resonance-like structures disappear already by $1.2T_c$
- strong threshold enhancement above free case

 => indication of correlations

- height of bump in lattice and model are similar

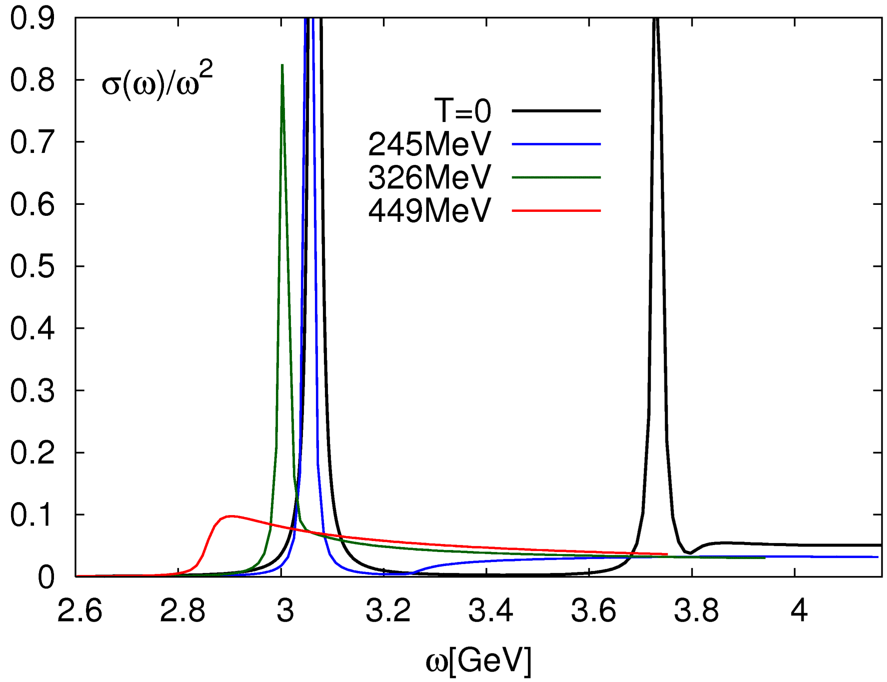
- The correlators do not change significantly despite the melting of the bound states => it is difficult to distinguish bound state from threshold enhancement in lattice QCD

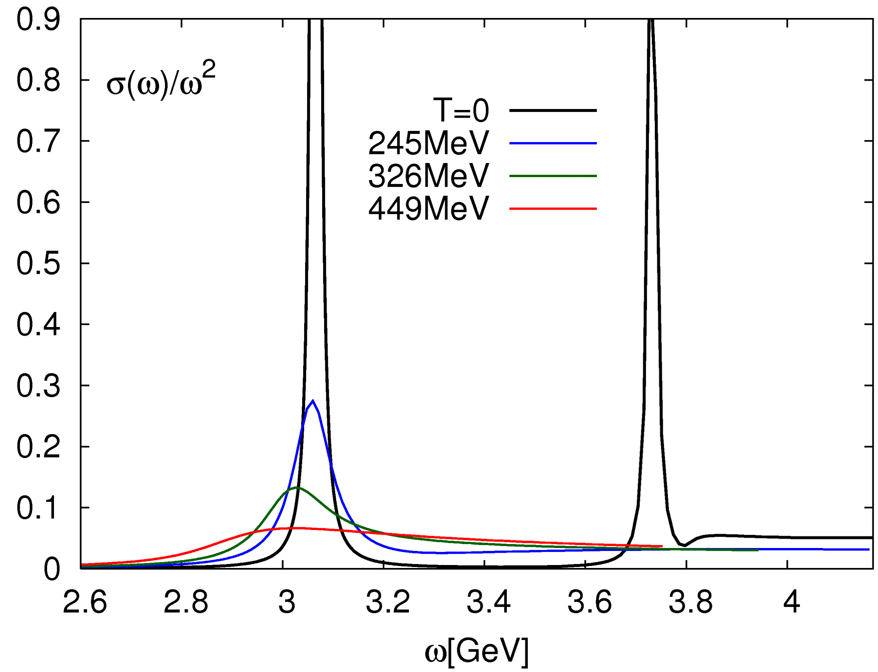
The role of the imaginary part for charmonium

Take the upper limit for the real part of the potential allowed by lattice calculations

Mócsy, P.P., PRL 99 (07) 211602,

Im $V_s(r) = 0$:
1S state survives for $T = 330$ MeV





imaginary part of $V_s(r)$ is included :
all states dissolves for $T>240$ MeV

Take the perturbative imaginary part
of the potential and the code from
Burnier, Laine, Vepsalainen JHEP 0801 (08) 043

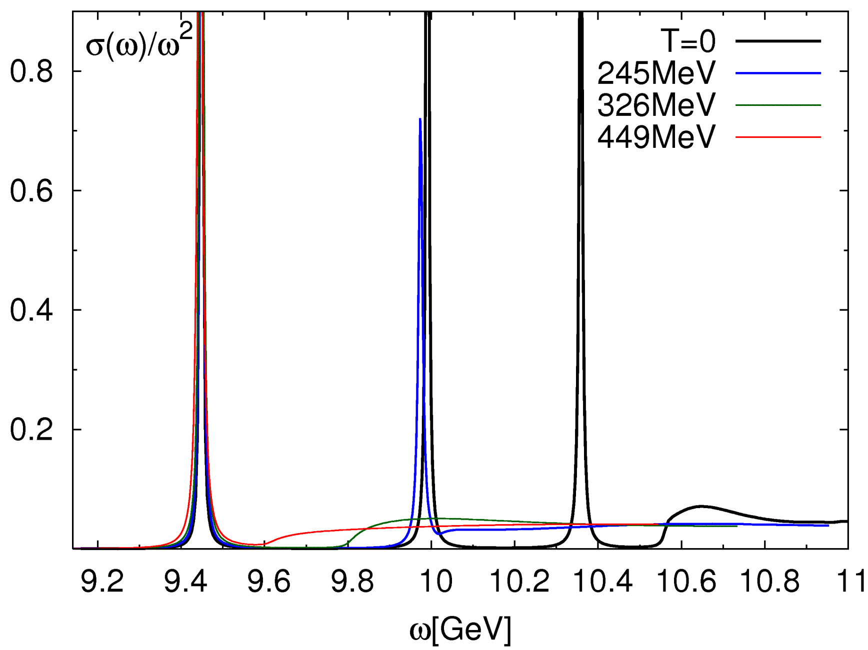
no charmonium state could survive for $T> 240$ MeV

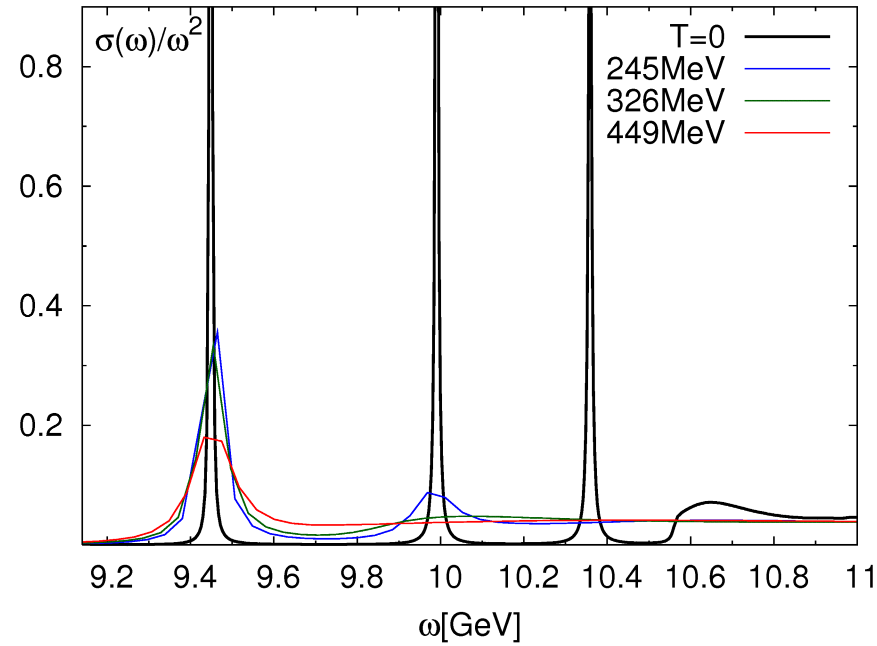
The role of the imaginary part for bottomonium

Take the upper limit for the real part of the potential allowed by lattice calculations

Mócsy, P.P., PRL 99 (07) 211602,

Im $V_s(r)=0$:
2S state survives for $T > 245$ MeV
1S state could survive for $T>450$ MeV





with imaginary part:
2S state dissolves for $T>240$ MeV
1S states dissolves for $T>450$ MeV

Take the perturbative imaginary part
the potential and the code from
Burnier, Laine, Vepsalainen JHEP 0801 (08) 043

no bottomonium state could survive for $T> 450$ MeV

Dynamical model for charmonium suppression at RHIC

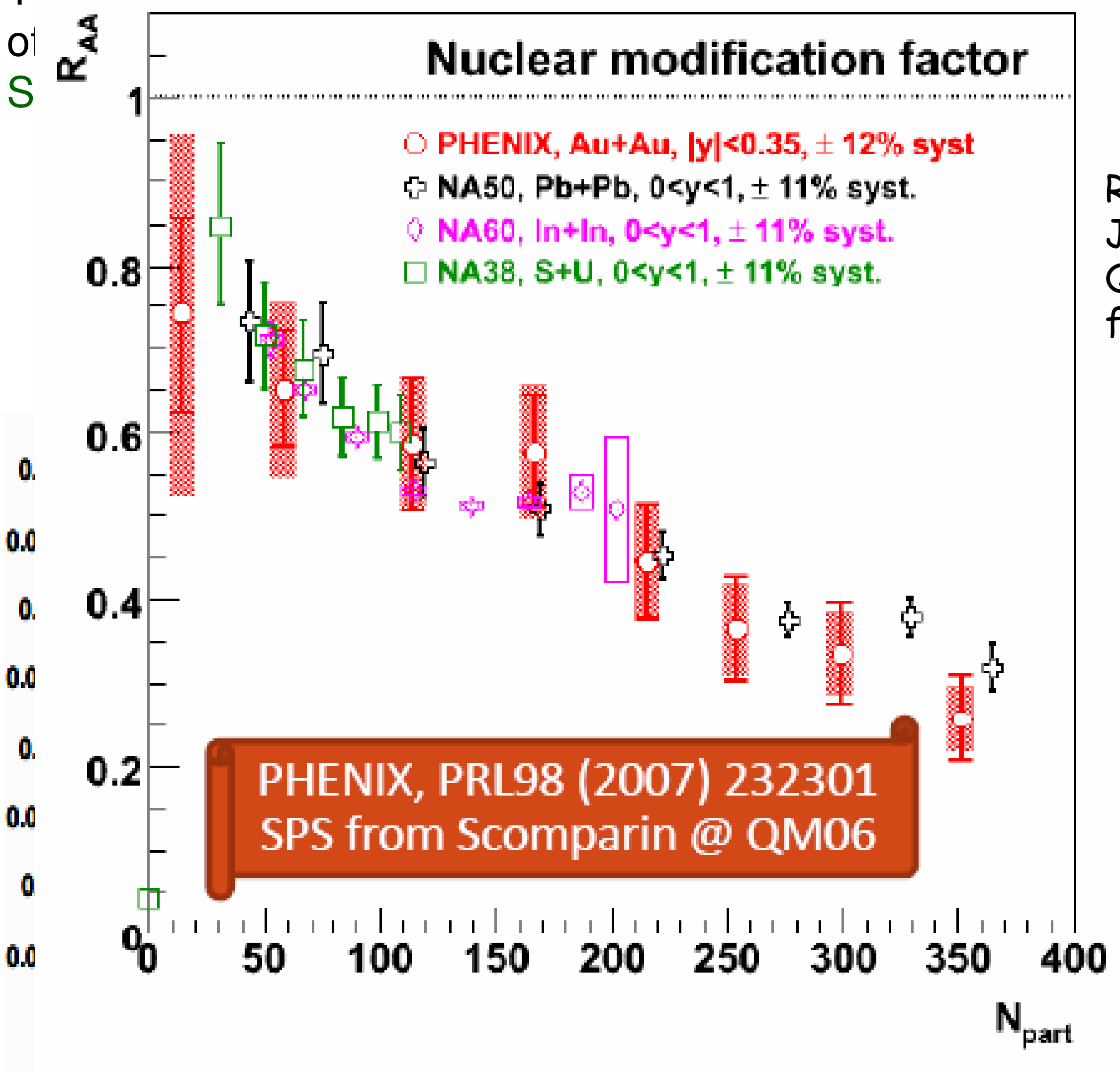
If the there are no $c\bar{c}$ bound states for T achieved at RHIC why $R_{AA}>0.2$?

Charmonium is formed inside the deconfined medium (QGP formation < *1fm* @ RHIC)

T... in-medium interaction

o... arm diffusion (drag)

S



R. Granier de Cassagnac,
Joint CATHIE-INT mini program
Quarkonium in Hot Media:
from QCD to Experiment, June 2009

...between quark and anti-quark

...nt from analysis of open charm yield

...ey, PRC71 (05) 064904

...r is simulated by *(2+1)d* hydro (*ε=p/3*)

...n lattice QCD an initial charm

...om PYTHIA

...of QGP at RHIC is not long
...mpletely de-correlate the initially
...ark anti-quark pairs

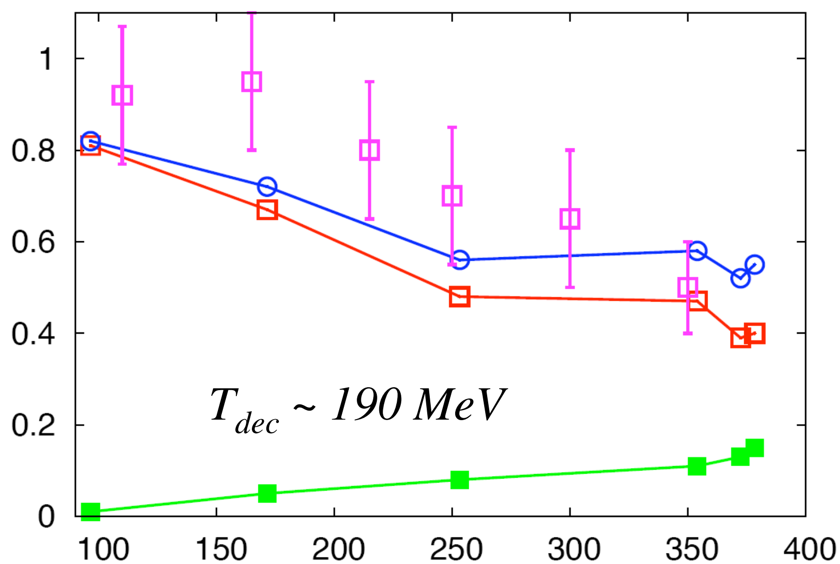
..., PRC 79 (09) 03490; arXiv:0911.3080

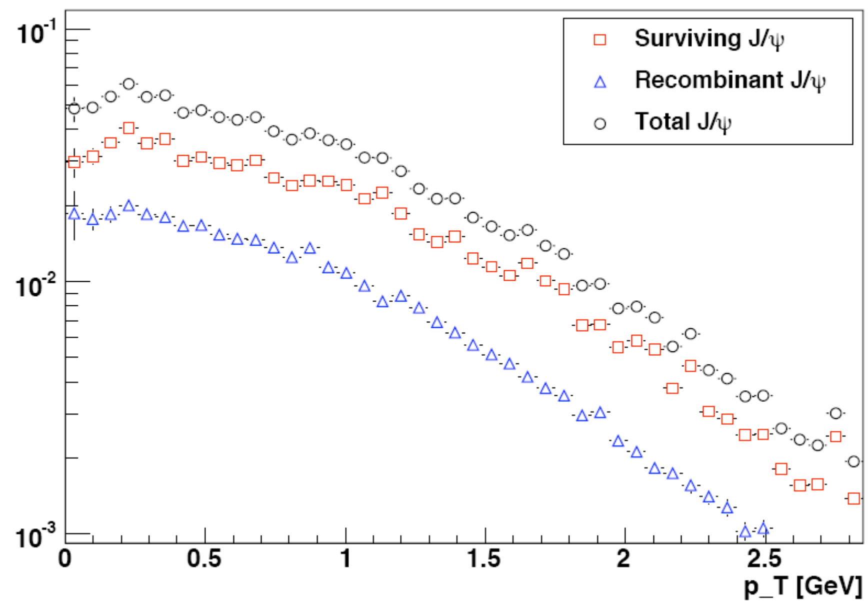
Dynamical model for charmonium suppression at RHIC

Both correlated and recomninant charmonium production can be calculated

For the 1st time there is a ab-initio calculation of recombinant charmonium production which turns out to be small at RHIC !

Young, Shuryak, PRC 79 (09) 03490; arXiv:0911.3080





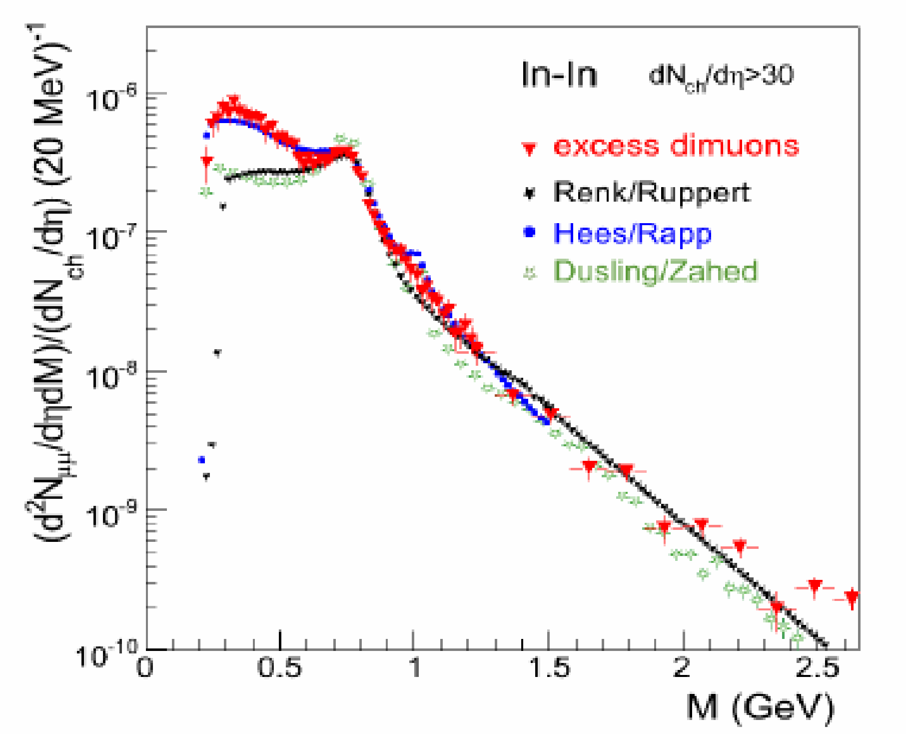
The model can explain the PHENIX data, despite the absence of bound there is only moderate suppression because the interaction of heavy quarks with each other and with the medium is significant

Thermal dileptons at SPS

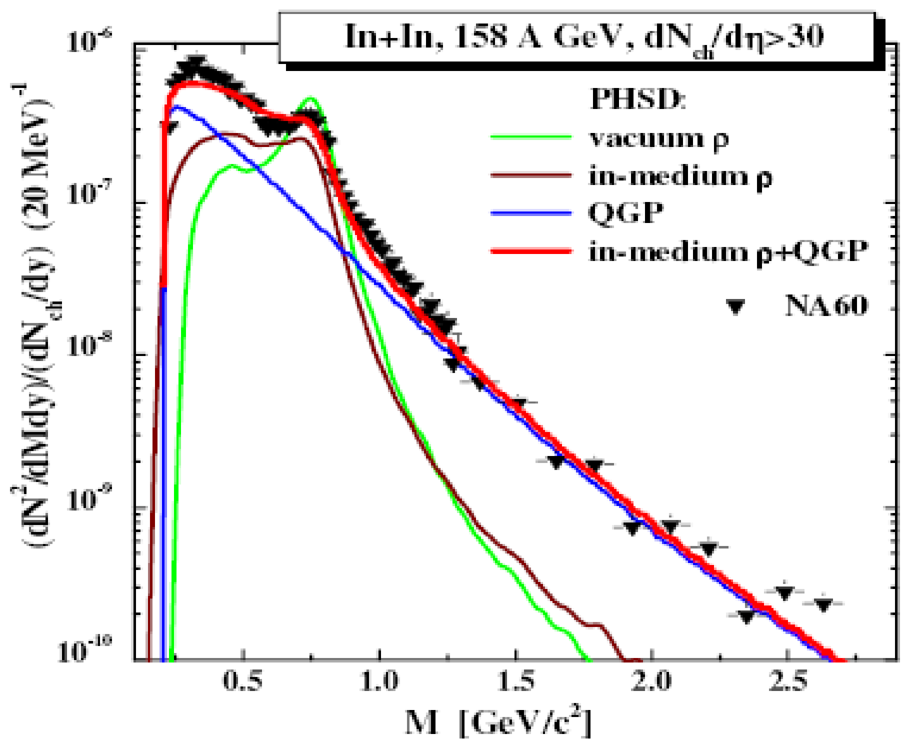
In the low mass region (LMR) excess dileptons are due to the in-medium modivications of the ρ-meson melting induced by baryon interactions

Models which incorporate this (Hess/Rapp and PHSD) can well describe the NA60 data !

NA60 : Eur. Phys. J 59 (09) 607
CERN Courier. 11/2009
fireball models and hydro model (Dusling/Zahed)



Linnyk, Cassing, microscopic transport
PHSD model, talk at Hard Probes 2010

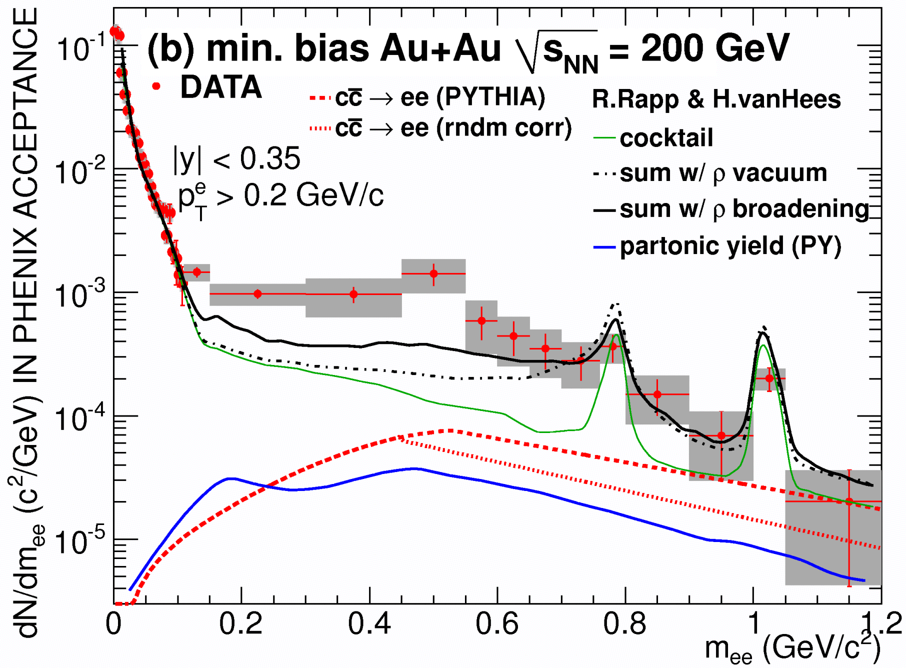


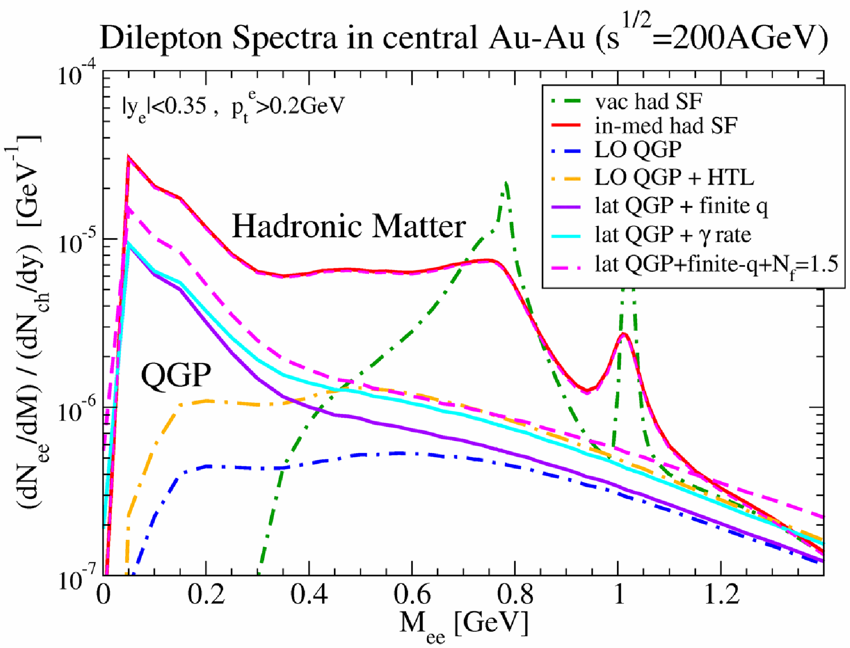
There is also an excess in the intermediate mass region (IMR) which could have partonic origin (D/Z, R/R, PHSD) or hadronic (H/R, $\pi a_1 \rightarrow \mu^+\mu^-$)

Thermal dileptons at RHIC and LMR puzzle

Models that described the SPS dilepton data fails for RHIC in low mass region !

Rapp, arXiV:1010.1719





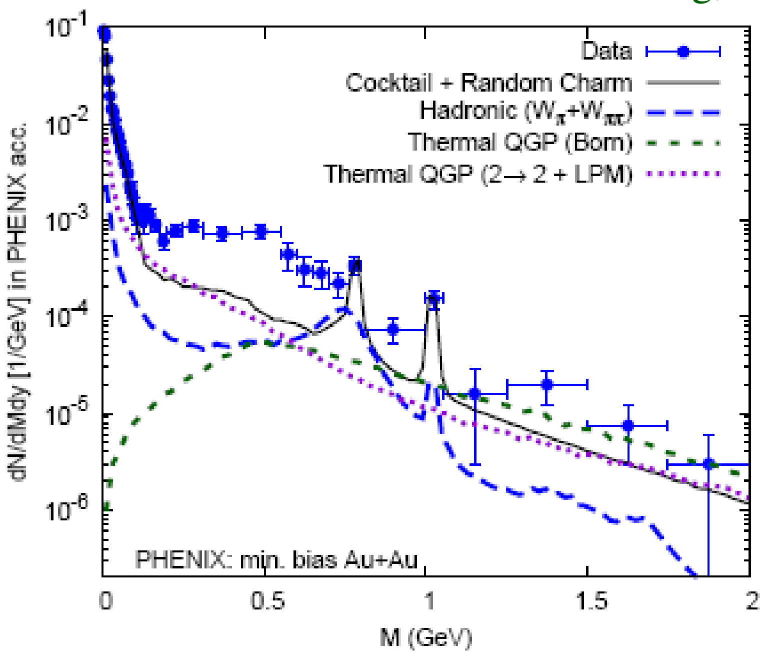
In the low mass region hadronic contribution dominates because of the larger 4-volume but there is large uncertainty in the QGP rate

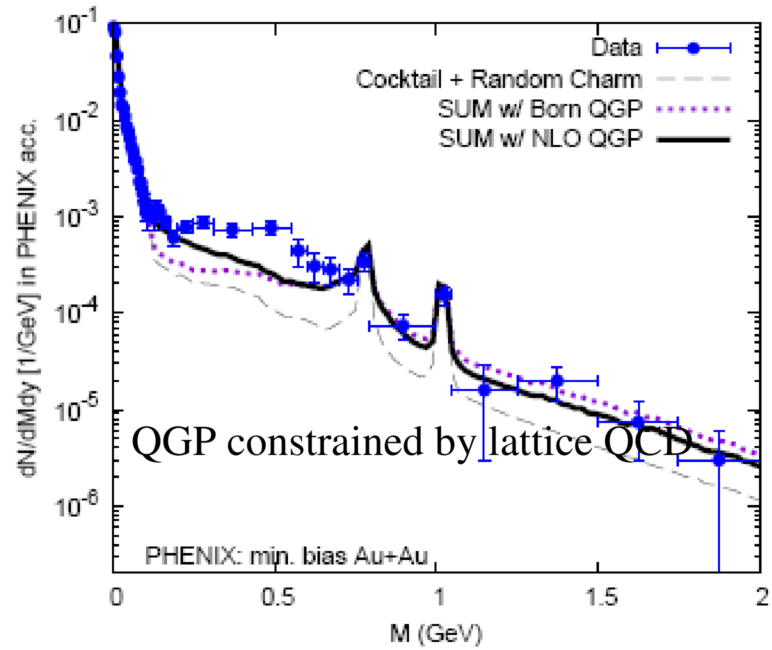
new lattice QCD based estimates are much larger than the perturbative QGP rates but cannot solve the LMR dilepton puzzle

⇨ more is going on in the broad transition region (~50MeV from the new lQCD results)

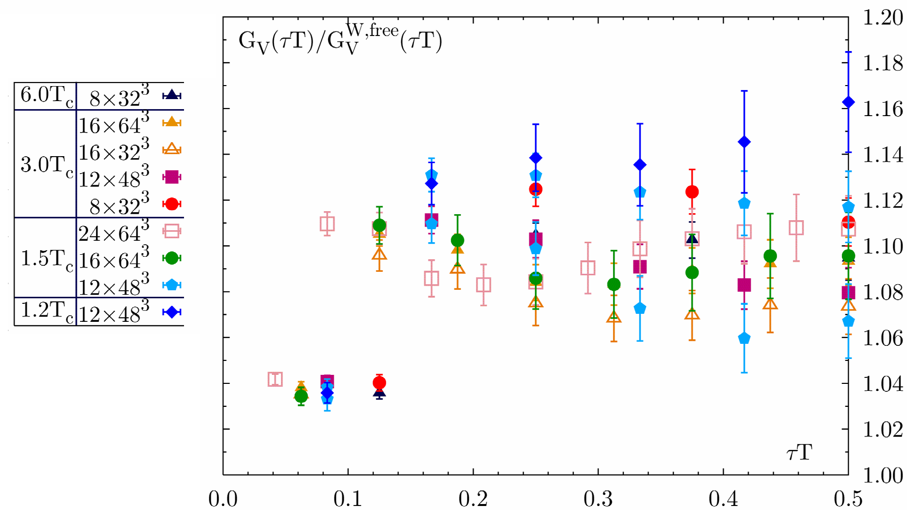
Thermal dileptons at RHIC and unceratinties in the QGP rates

Dusling, Zahed, arXiv:0911.2426





Dilepton rate is constrained by lattice QCD



Kinematic effects are important
in the low mass region

NLO QGP rate >> LO (Born) QGP rate

One needs, however, at least an order of magnitude larger QGP rate to explain the data

Also in the IMR there is potentially a factor 2 uncertainty in the QGP rate

Born rate ~ 2x NLO rate

Summary

• Temporal meson correlation function are not sensitive to the medium modification of the quarkoniuum spectral functions, but the spatial meson correlation functions provide the 1st direct lattice QCD evidence for melting of the 1S charmonium for *T>300* MeV consistent with color screening

• EFT approach provides an framework to discuss systematically the problem of quarkonium melting at finite temperature and static potentials can be defined. Due to the the imaginary part of the potential we have dissolution of the *1S* charmonium and excited bottomonium states for $T \approx 250$ MeV and dissolution of the *1S* bottomonium states for $T \approx 450$ MeV.

• However, residual interaction of heavy quarks and strong in-medium drag preserve the initial correlations and lead to formation of charmonium states in the transition region and roughly can explain the $R_{AA}(J/\psi)$ at RHIC

The recombinant J/ψ production was calculated from 1st principles by Yound and Shuryak and was found to be small

• The thermal dilepton production at SPS can be understood in terms of in-medium rho meson melting and QGP radiation for IMR. However, all models fail for RHIC for LMR

• There large uncertainties in the QGP dilepton rates, however, this is unlikely to explain the RHIC LMR dilepton puzzle, we need to understand the physics in the transition region

thanks to R. Rapp and K. Dusling for correspondence